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Citation for published version:
Lavallée, Y, Hirose, T, Kendrick, JE, Hess, KU & Dingwell, DB 2015, 'Fault rheology beyond frictional melting', *Proceedings of the National Academy of Sciences*, vol. 112, no. 30, pp. 9276-9280. https://doi.org/10.1073/pnas.1413608112

Digital Object Identifier (DOI):
10.1073/pnas.1413608112

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Publisher's PDF, also known as Version of record

Published In:
Proceedings of the National Academy of Sciences

Fault rheology beyond frictional melting

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Edited by Bruce Watson, Rensselaer Polytechnic Institute, Troy, NY, and approved June 1, 2015 (received for review July 23, 2014)

During earthquakes, comminution and frictional heating both contribute to the dissipation of stored energy. With sufficient dissipative heating, melting processes can ensue, yielding the production of frictional melts or "pseudotachylytes." It is commonly assumed that the Newtonian viscosities of such melts control subsequent fault slip resistance. Rock melts, however, are viscoelastic bodies, and, at high strain rates, they exhibit evidence of a glass transition. Here, we present the results of high-velocity friction experiments on a well-characterized melt that demonstrate how slip in melt-bearing faults can be governed by brittle fragmentation phenomena encountered at the glass transition. Slip analysis using models that incorporate viscoelastic responses indicates that even in the presence of melt, slip persists in the solid state until sufficient heat is generated to reduce the viscosity and allow remobilization in the liquid state. Where a rock is present next to the melt, we note that wear of the crystalline wall rock by liquid fragmentation and agglutination also contributes to the brittle component of these experimentally generated pseudotachylytes. We conclude that in the case of pseudotachylyte generation during an earthquake, slip even beyond the onset of frictional melting is not controlled merely by viscosity but rather by an interplay of viscoelastic forces around the glass transition, which involves a response in the brittle/solid regime of these rock melts. We warn of the inadequacy of simple Newtonian viscous analyses and call for the application of more realistic rheological interpretation of pseudotachylyte-bearing fault systems in the evaluation and prediction of their slip dynamics.

earthquake slip | frictional melting | obsidian breccia | cataclasite | pseudotachylyte

Explicit and detailed knowledge of the thermomechanics of geomaterials subjected to frictional work during slip events is an essential basis for the modeling of earthquake dynamics. Dynamic slip events are generally described using constitutive laws of rate-and-state-dependent friction, often cast in terms of aging factors (1, 2). Such time dependence of slip behavior has, for example, been related to the increased interfacial bonding of asperity contacts resulting from creep (3) and/or chemical diffusion (4). It has been further proposed, however, that friction-dominated systems undergo dynamic slip weakening at coseismic slip rates (>0.1 m/s) through one or more of several causative pathways, including flash heating (5), thermal pressurization (6), chemical decomposition (7, 8), silica gel formation (9, 10), and, in the extreme, frictional melting (11, 12). The occurrence of frictional melting, preserved in the geological record as pseudotachylytes (13–15), is generally interpreted as an indicator of coseismic slip events (14). Beyond the point of frictional melting, it has been generally assumed that Newtonian melt viscosities can be used to constrain the dynamics of slip and thereby the subsequent evolution of an earthquake (12, 16–18).

All molten rocks, indeed, all liquid silicates, exhibit a glass transition, where the stress–strain relationship is defined as viscoelastic (19). The glass transition itself is a transition from liquid-like to solid-like strain response of a melt. In the fully relaxed state, silicate liquids behave as Newtonian fluids. At high strain rates and/or upon cooling, that is, as the glass transition is approached, structural relaxation may not be achieved, so that structural breakdown of the liquid may yield a non-Newtonian response and, ultimately, failure. Decades of research on silicate liquids have provided us with a rather complete description of their viscosity and glass transition (20) as a function of chemical composition (21).

Frictional melting of rocks has been constrained to be a disequilibrium process, which involves selective melting of the mineral phases (22, 23). Upon further slip, forced convection of the so-generated melts enhances mixing and homogenization of the melt along a fault plane (12). The complex and transient nature of frictional melts makes their rheological description difficult. Unlike molten rocks generated by friction, the melt resulting from a glass as it liquefies at the glass transition undergoes no chemical changes. Upon approaching the glass transition, the structure of a glass begins to seek a state of local equilibrium with respect to temperature and pressure conditions via configurational changes in its structure. This relaxation of state, achieved through self-diffusion, is accompanied by a relaxation of physical stresses in the system (24). One consequence of the onset of such stress relaxation upon heating is typically a near tripling of volumetric expansivity at the glass transition (25). Upon viscous remobilization, the system adopts the state of a homogeneous liquid phase. Pure, single-phase glasses are thus an ideal material to test the rheology of melt present in slip zones.

Materials and Methods

What role does melt play in fault friction? To answer this question, we have assessed the mechanics of slip during frictional "melting" by experimentally recording the behavior of glass itself during frictional heating, up to and beyond the glass transition temperature. (Here, the classical term, melting, denotes the viscous remobilization of glass across the glass transition, as a glass does not melt but softens, relaxes, or liquefies.) High-velocity friction experiments were performed in a low- to high-velocity rotary shear apparatus on well-characterized standard borosilicate glass (NIST 717a). This glass, with homogeneous melt chemistry and a well-known viscosity–temperature

Significance

During an earthquake, the mechanical work of friction along the fault is partly dissipated as heat, which results in rock melting and pseudotachylyte generation along the fault plane. Beyond this point, it is generally believed that Newtonian viscous forces regulate slip. Molten rocks are, however, viscoelastic bodies exhibiting the so-called glass transition of liquid-like to solid-like response to stresses that allows the melt itself to fracture. This simple fact, the significance of which is demonstrated in high-speed frictional melting experiments, redefines fault slip rheology in major earthquakes.

Author contributions: Y.L. and D.B.D. designed research; Y.L., T.H., J.E.K., and D.B.D. performed research; Y.L. and T.H. contributed new reagents/analytic tools; Y.L., J.E.K., and K.-U.H. analyzed data; and Y.L., T.H., J.E.K., K.-U.H., and D.B.D. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Freely available online through the PNAS open access option.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1413608112/-/DCSupplemental.

Table 1. Thermomechanical data

Test number	Sample	Normal stress, MPa	Slip velocity, $m \cdot s^{-1}$	Observation	Heating rate at Tg, $°C \cdot s^{-1}$	Tg_{cal}, °C	Tmax, °C	Log viscosity at Tg_{cal}, Pa·s
3184	glass–glass	1.5	0.53	rapid failure	—	—	454	—
2920	glass–glass	1.5	0.80	failure at Tg	281	682	680	7.35
3165	glass–glass	1.5	1.28	failure at Tg	419	691	927	7.19
3166	glass–glass	1.5	1.44	weld and fail	870	708	670	6.85
3167	glass–glass	1.5	1.44	failure at Tg	405	690	777	7.19
2921	glass–glass	1.5	1.60	weld	650	701	1,046	6.98
3186	glass–glass	5.0	0.80	failure at Tg	379	689	672	7.21
3182	glass–glass	5.0	1.44	rapid failure	—	—	282	—
3183	glass–glass	5.0	1.44	rapid failure	—	—	191	—
3168	glass–glass	5.0	1.60	weld	1,022	712	959	6.78
2922	glass–gabbro	1.5	0.80	failure at Tg	175	671	667	7.58
3185	glass–gabbro	1.5	1.28	weld and fail	540	697	733	7.06
2923	glass–gabbro	1.5	1.60	weld	695	702	908	6.96
3187	glass–gabbro	5.0	0.80	failure at Tg	372	689	666	7.21
3169	glass–gabbro	5.0	1.60	weld	751	705	802	6.91

Tg calculated is the glass transition temperature constrained by the heating rate, and Tmax relates to the maximum temperature emitted along the slip zone of a sample. For samples that rapidly failed, the temperature did not reach the glass transition interval, which prevented viscoelasticity analysis.

relationship, permits an accurate rheological assessment of the liquid vs. solid-state response. Experiments were conducted on hollow cylindrical samples with outer and inner diameters of 24.99 mm and 15.86 mm, respectively. The samples were axially loaded at the desired normal stress (1.5 and 5.0 MPa) by an air-actuator and slip was applied via a servo motor operated at 500, 750, 1,200, 1,350, or 1,500 rotations per minute, corresponding to slip rates of 0.5–1.5 m/s. In this study, the glass-on-glass experiments were complemented by glass-on-rock tests using a microcrystalline gabbro.

Glass-on-Glass Friction

Friction experiments were conducted on a pair of glass samples at slip velocities between 0.5 and 1.5 m/s and normal stresses of 1.5 and 5 MPa (Table 1). The dynamic slip was accompanied by a rapid peak in shear resistance (Fig. 1) and, visually, by the development of cracks near the slip surface (see Movies S1 and S2). Experiments at low applied stresses and/or slip rate showed a tendency to undergo complete failure and fragmentation as the sample started to radiate incandescently and the slip zone exhibited incipient liquid behavior (Movie S1). At high applied stresses and/or slip rate, the glass remained intact long enough to melt, viscously remobilize, and weld the surface, allowing slip to reach greater distances (Movie S2). The data obtained constrain the origin of successful viscous remobilization to specific mechanical conditions that are accentuated by increases in normal stress or slip velocity (Table 1). Even in the presence of a liquid layer, slip commonly induced failure of the liquid within ~1 s. Optical analyses of samples thus remobilized indicate that the slip zone is marked by striations (Fig. 2). These would appear to indicate that, despite late viscous remobilization on either side of the slip zone, slip remained localized along the interface for a prolonged period, which we hypothesize resulted from the solid-state behavior of the glass specimens even at high temperatures, due to the high strain rate. Examination of the viscously remobilized portion of the slip zone shows that it hosts partially healed glass shards, clear evidence of a mixture of viscous and brittle response, where sample failure appears to have initiated via a system of tensile cracks propagating orthogonally out from the slip surface (Fig. 2).

Thermomechanical Analysis

Thermal imaging (at 16 frames per second) of the exterior of the samples, showing the outer edge of the sample interface, was used to constrain the thermomechanical state of glass during slip (see *SI Text* and Fig. S1). Frictional heating occurred at a very high rate along the slip surface at the onset of sliding, which slowed progressively as the sample temperature increased and ultimately reached a dynamic thermal equilibrium (Fig. 1). In the immediate vicinity of asperities, local thermal anomalies developed (Fig. S2); these samples showed a tendency to break rapidly without reaching high temperatures. Most samples managed to reach high temperatures (Table 1). The samples that crossed the calculated glass transition temperature, Tg_{cal}, underwent further heating before initiation of viscous remobilization (see experiments at 1.6 m/s in Fig. 1).

Thermomechanical analysis of the monitored data provides insight on the mechanisms underlying slip, viscous remobilization, and glass failure (see *SI Text* for detail of the methods). As the glass transition of amorphous material reflects the kinetics of the transition from solid to liquid state, the temperature (and thus the viscosity and structural relaxation rate) at the glass transition can be constrained by knowing the heating rate through the glass transition interval (24, 26). The results of such an analysis are striking. We find that failure occurs precisely at the glass transition for experiments in which glass heats at a rate below 400 °C/s (Fig. 3). For experiments with higher heating rates (i.e., at faster slip rate and/or higher axial stress), the glass transition temperature estimated from the heating rate is exceeded without instantaneous viscous remobilization; further temperature increase is required to reduce the viscosity sufficiently to successfully cross the glass transition and prompt viscous remobilization. The 400 °C/s barrier marks a viscosity of $\sim 10^{7.2}$ Pa·s at the glass transition. Maxwell's law of viscoelasticity relates the relaxation timescale of a liquid structure (τ) to its shear viscosity (μ) and shear modulus at infinite frequency (G_∞) according to

$$\tau = \mu / G_\infty . \quad [1]$$

In this formulation, viscosity is the primary variable controlling the structural relaxation timescale, as G_∞ can be approximated to 10^{10} Pa for a wide range of temperatures and silicate liquid compositions (19). The nondimensionality of strain allows us to rewrite this equation to estimate the maximum strain rate (γ_{max}) applied to a liquid of a given viscosity (in order for it not to break) via the simple reciprocal consideration

$$\gamma_{max} = 1/\tau . \quad [2]$$

It has been experimentally demonstrated that structural breakdown and failure of silicate liquid initiates some two orders of

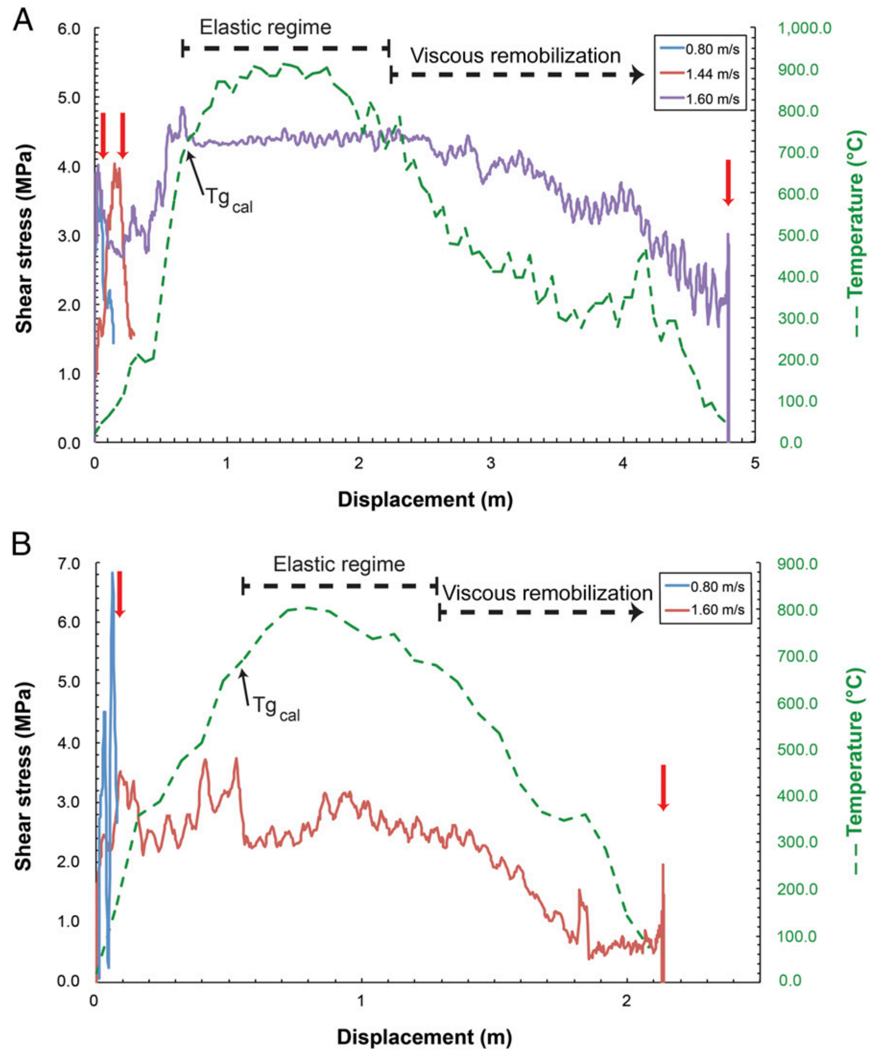

Fig. 1. Thermomechanical responses of glass subjected to frictional work. The data show (*A*) glass-on-glass and (*B*) glass-on-rock friction at high slip velocities and under 5.0 MPa of applied normal stress. The red arrows denote sample failure. The mechanical responses at 1.6 m/s are characterized by crossing the calculated glass transition, Tg_{cal}, without failure due to rapid heating. Beyond Tg_{cal}, displacement of the frictional liquid is initially experienced as slip in the glassy, elastic regime, followed by relaxation and viscous remobilization, allowing for shear weakening and, ultimately, failure. Thermal data for the experiments at 0.8 m/s and 1.44 m/s were omitted for legibility of this plot, as the thermal information of the test at 1.6 m/s is most informative.

magnitude of strain rate below that predicted by Maxwell's theory (19); the maximum strain rate that can possibly be applied to a liquid without failure thus approximates

$$\gamma_{max} = {}^{10^8}/_{\mu}. \qquad [3]$$

In a dynamic slip scenario, in which a fault zone hosts frictional melt, the shear strain rate equates the ratio of slip velocity to fault thickness (d). We can thus rewrite these equations to obtain the maximal slip rate viscously accommodated during faulting in the presence of a frictional melt layer (v_{max}),

$$v_{max} = 10^8 \cdot {}^{d}/_{\mu}. \qquad [4]$$

For our example where the liquid is estimated at $10^{7.2}$ Pa·s and fault thickness is observed to approximate 0.1 mm, application of Eq. 4 yields a maximum slip rate of $10^{-2.8}$ m/s. This slip rate limit is exceeded by the imposed slip rate conditions of ∼1 m/s. This analysis suggests that the slip undergone upon melting (i.e., crossing of the glass transition by heating) is briefly accommodated by slip in the solid regime, thereby generating frictional striations along the slip axis and causing frictional heating. Temperature increase beyond the calculated glass transition accelerates the relaxation process by up to four orders of magnitude and transforms the glassy response of the samples along the slip interface into viscous deformation. As heat dissipates into the surrounding material, heating it above its glass transition, viscous deformation of the Newtonian fluid serves to homogeneously distribute strain across a broader shear zone, which corresponds to a decrease in shear resistance (after 3 m slip, Fig. 1).

Glass-on-Rock Friction

To assess whether the above observation (that slip may take place in the solid state when a melt is present in the slip zone) is applicable in the presence of natural rock, we performed heterogeneous friction experiments using glass against microcrystalline gabbro (see ref. 12). Once again we find that the thermal path leading to the glass transition dictates the fate of the slip zone; a heating rate of >400 °C/s appeared once more to be a threshold to the ability of glass to viscously remobilize (Figs. 1 and 3). In these experiments, the gabbro did not melt, but rather underwent

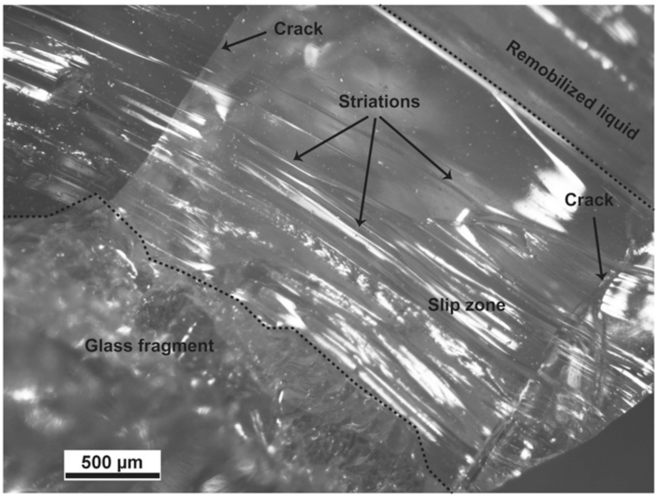

Fig. 2. Photograph of the slip zone in plane view. The slip zone exhibits striations and is bordered by a zone of remobilized melt on the outer margin and a welded glass fragment on the inner margin. The slip zone is crosscut by orthogonal cracks developed at ∼2-mm intervals.

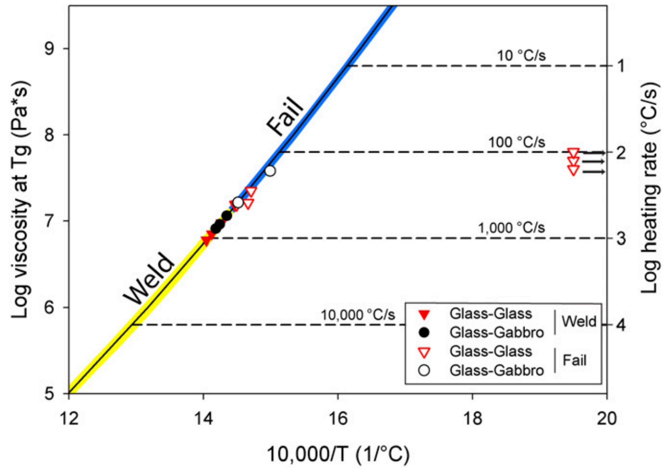

Fig. 3. Thermomechanical analysis of melt rheology in the slip zone. The data are plotted on the basis of temperature at which glass reached Tg_{cal} and the heating rate in the glass transition interval (see Table 1). The data overlaps with the solid curve defining the viscosity at Tg. We note that a heating rate of 400 °C/s (which corresponds to a temperature of 690 °C and a viscosity of $10^{7.2}$ Pa·s) discriminates between samples that successfully met the glass transition and viscously remobilized (filled symbols) and those that failed (empty symbols). We highlight these different mechanical regimes where the melts fail in the slip zone (in blue) or remobilize and weld the slip zone (yellow).

significant wear by shear from the neighboring high-viscosity liquid. This results from the relatively low temperature of the glass transition of the tested material with respect to the high melting temperature of the gabbro. However, the conclusion remains. The strong and highly brittle response of silicate melts makes distributed viscous flow a largely improbable mode of mechanical response if the viscosity or stress is too high or if slip rate is too fast.

The rheological analysis proposed in Eq. 4 can be readily applied to a range of experimental and natural scenarios to evaluate the state of frictional melt and thus constrain the mode of deformation controlling earthquake slip, be it brittle fragmentation and cataclasis or viscous remobilization and flow. The brittle response of frictional melts may be particularly common if a fault hosts a thin melt zone, if slip takes place in rocks with relatively low melting temperatures, or if the frictional melts have relatively high viscosities due to their chemistry or due to low temperature in the waning stage of a faulting event. Breccias and cataclasites have been noted in a number of pseudotachylytes (27, 28), and their exact origin remains debated (29), although they have been constrained to form at similar conditions (23). Here we suggest that the viscoelastic nature of frictional melt may prompt failure during certain fault slip conditions, which may be at the origin of their adjacencies in fault zones; this may explain observation of fault structures hosting coeval pseudotachylyte, cataclasite, and breccia. Melt failure has been noted in stick-slip experiments (30) as well as in volcanic environments, such as at the margin of shallow obsidian dykes (31), and we argue that it may be more common than previously anticipated in tectonic fault zones. We urge the reexamination of brecciated pseudotachylyte to reassess the origin of their brittle behavior.

Conclusions

Friction tests performed on standard glass provide unequivocal evidence for extraordinary behavior, in which viscous forces alone cannot control the rheology of earthquake slip in the presence of a frictional melt phase. The experimental results highlight the importance of brittle response of the frictional melt during dynamic slip. In the glassy frictional phase before viscous remobilization, a contribution both from comminution and from preferential friction of asperity contacts perturbs the frictional slip behavior. This favors localized thermal anomalies and leads to catastrophic failure. In an apparent paradox, if frictional melting is achieved, then the fate of slip nevertheless appears initially bound to the kinetics of friction in a solid state. This is because samples that successfully thermally overshot the calculated glass transition (at >400 °C/s) underwent slip in the glassy (solid-like) regime until sufficient subsequent heating enabled structural relaxation and initiated viscous remobilization, bringing with it the possibility of healing and, sometimes, failure. It is due to the presence of this kinetic barrier, the glass transition, that the friction of melt almost invariably exceeded the brittle limit of the glass and/or the liquid, precipitating failure in our experiments. These properties are unique among molten geomaterials. The glass transition appears to make inevitable the fact that under extreme slip conditions, frictional melt behaves more like a solid than a viscous liquid. We conclude that in the case of extreme frictional slip dynamics, frictional melts may undergo severe brittle fragmentation and the earthquake rheology may momentarily encompass cataclastic flow of melt fragments, both of which demand of us a fundamental reassessment of pseudotachylyte structures as well as models of fault rheology during earthquakes.

ACKNOWLEDGMENTS. We thank H. Mukoyoshi for technical assistance. T.H. acknowledges the Japan Society for the Promotion of Science (JSPS) for funding the Grants-in-Aid for Scientific Research (KAKENHI, 25287135). D.B.D. acknowledges the support of European Research Council (ERC) Advanced Researcher Grant on Explosive volcanism in the earth system: experimental insights (EVOKES, 247076) and Y.L. acknowledges an ERC Starting Grant on Strain Localisation in Magmas (SLiM, 306488).

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